concawe

ENVIRONMENTAL SCIENCE FOR THE EUROPEAN REFINING INDUSTRY

Effects of diesel fuel specification properties on particulate emissions in Euro 4, 5 and 6 passenger cars

R. Williams[1], H. Hamje[2], A. Dimaratos[3], D. Rickeard[4], J. Ariztegui[5], P. van de Heijing[6], K. Kar[7], G. Gunter[8], C. Fittavolini[9], P. Ziman[1] K. Lehto[10], Z. Samaras[3], T. Bartsch[11]

1 Shell Global Solutions, 2 concawe, 3 Laboratory of Applied Thermodynamics, Aristotle University of Thessaloniki, 4 Independent consultant, 5 Repsol, 6 Q8, 7 ExxonMobil, 8 Phillips 66, 9 ENI, 10 Neste Oil, 11 BP.

concawe
ENVIRONMENTAL SCIENCE FOR THE EUROPEAN REFINING INDUSTRY

Contents

concawe
ENVIRONMENTAL SCIENCE FOR THE EUROPEAN REFINING INDUSTRY

Background & Aims

- EN590 has been developed taking into consideration environmental and economic effects of fuel sourcing, manufacturing and finished fuel quality as well as maximising the efficient operability of diesel fired vehicles.
- Diesel fuel properties were found to affect vehicle emissions in previous studies with older technology vehicles.
- Properties identified in the Fuel Quality Directive (FQD) as environmental parameters include Polycyclic Aromatic Hydrocarbons (PAH), density and Cetane Number (CN).
- Fatty Acid Methyl Ester (FAME) content is another important consideration given its potential to help meet the Renewable Energy Directive (RED) targets.
- As vehicles evolve & fuel stocks diversify it is prudent to re-evaluate the EN590 specification to ensure it remains fit-for-purpose.
- Concawe commissioned a study of the effects of PAH, density, CN & FAME on emissions & efficiency, including PM, PN, particle size distribution and particulate composition to determine how these effects manifest themselves in diesel vehicles spanning technologies comprising a large proportion of the current European fleet.

Contents

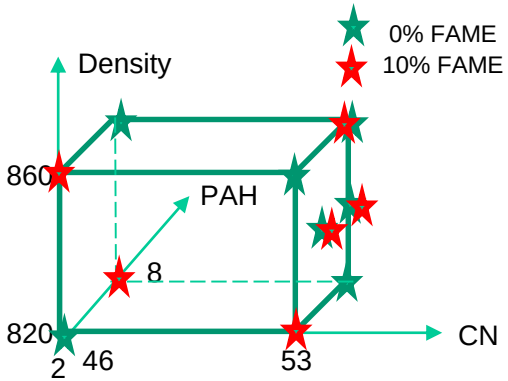
- Background & Aims
- **Test programme overview**
  - Vehicles
  - Fuels
  - Test equipment overview
  - Particle characterisation
  - Testing overview
  - Data handling
- Results
- Conclusions

Vehicles

Vehicle property	Euro 4	Euro 5	Euro 6
Inertia class	1590kg	1360kg	1130kg
Category	M1	M1	M1
Year of manufacture	2004	2013	2015
Displacement/output	2.2L/103kW	1.3L/70kW	1.6L/88kW
Transmission	Manual 5-speed	Manual 5-speed	Manual 6-speed
Fuel/charging system	Common rail / turbocharged	Common rail / turbocharged	Common rail / turbocharged
Exhaust gas treatment configuration	High Pressure Exhaust Gas Recirculation (HP EGR) + Diesel Oxidation Catalyst (DOC)	HP EGR + DOC + Diesel Particulate Filter (DPF)	HP EGR + DOC + Selective Catalytic Reduction (SCR) + DPF
Start of test mileage	89,850 miles	10,350 miles	10,300 miles

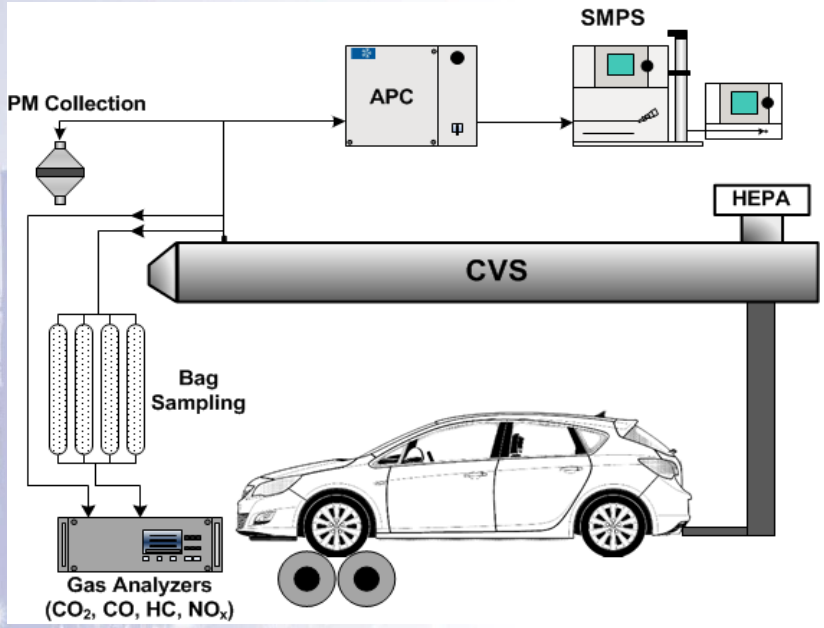
Fuels

Fuel	Density at 15° C (kg/m3)		PAH (%m/m)		FAME (%v/v)		Cetane Number	
	820	860	2%	8%	0%	10%	46	53
1	x		x		x		x	
2		x	x			x	x	
3		x	x		x			x
4	x		x			x		x
5		x		x	x		x	
6	x			x		x	x	
7	x			x	x			x
8		x		x		x		x
9		x		x	x			x
Fuel	840		4%	8%	0%	10%	53	
10	x			x	x		x	
11	x			x		x	x	
12	x		x		x		x	
13	x		x			x	x	



- A European EN590 <10ppm S B5 (fuel 14) was used as a reference.
- FAME was EN14214 compliant European RME.
- All fuel parameters were EN590 compliant except those being intentionally varied.
- Other than FAME, hydrocarbon blending components were used as far as possible to obtain property targets.
- 2-EHN was used to trim CN in some cases.

Test Equipment Overview

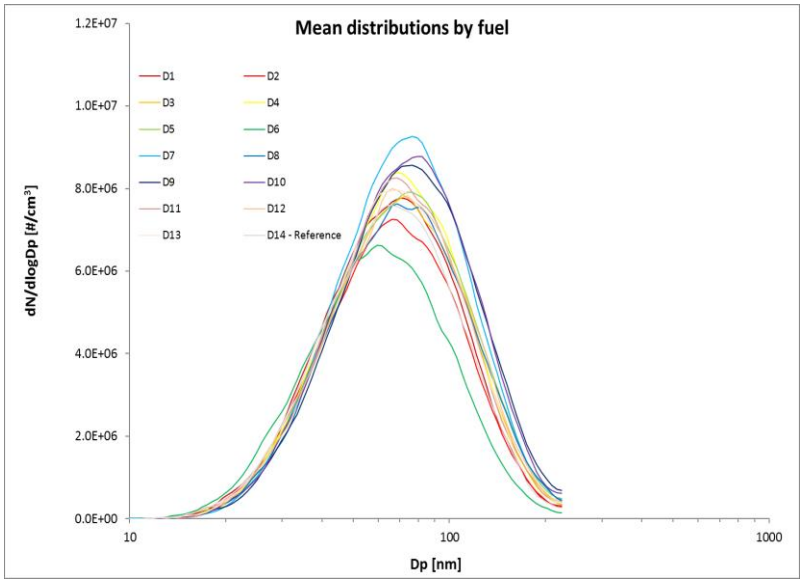


HEPA:
High Efficiency
Particulate Air filter

Conventional Chassis Dynamometer (CD) experimental set up with Constant Volume Sampling (CVS) of emissions

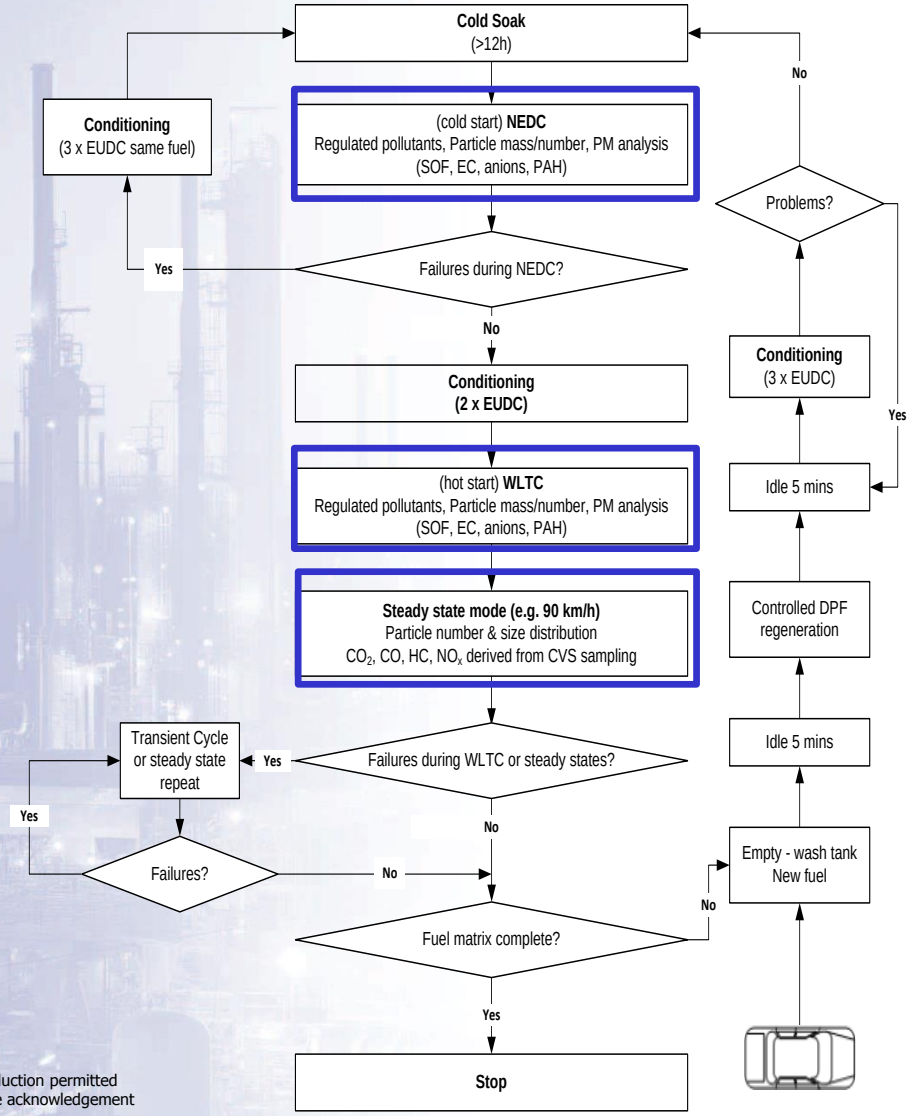
PM measurement: PTFE filters weighed before and after the test

PN measurement
- **A**VL **P**article **C**ounter (APC)
- VPR: Volatile Particle Remover with 2 stage dilution
- PNC: Particle Number Counter, n-butanol based condensation particle counter (CPC) with a cut-off diameter of 23 nm



Particle size distribution
- Scanning Mobility Particle Sizer (SMPS): TSI-3080 classifier and CPC 3776
- Basic component: Differential Mobility Analyzer (DMA)
- Particle size range: 6-225 nm

Testing Overview

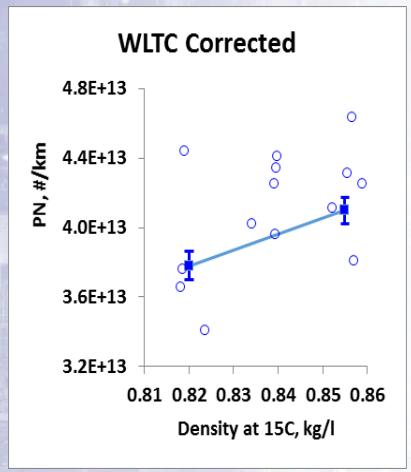


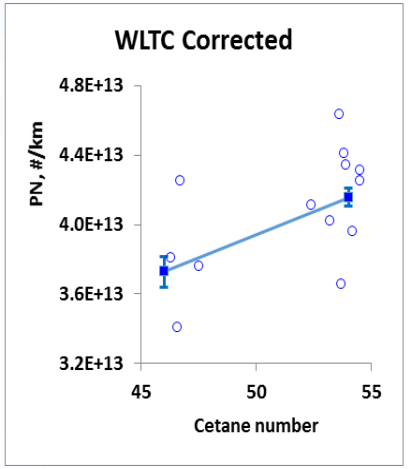
- Randomised test fuel sequence.
- Each fuel tested over 3 passes per vehicle.
- Additional reference fuel tests.

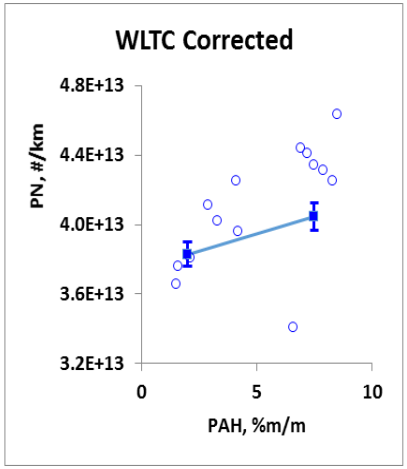
Test fuel order vehicle 1			Test fuel order vehicle 2		
pass 1	pass 2	pass 3	pass 1	pass 2	pass 3
(ref) 14	(ref) 14	(ref) 14	(ref) 14	(ref) 14	(ref) 14
7	12	6	13	5	12
10	5	1	6	1	7
12	9	10	4	11	6
1	6	11	8	7	2
8	1	7	5	10	8
3	(ref) 14	8	1	(ref) 14	5
(ref) 14	4	2	(ref) 14	6	13
13	2	(ref) 14	2	12	(ref) 14
9	7	4	9	3	11
5	11	13	11	4	4
2	8	9	3	2	9
6	13	3	12	13	10
4	3	12	7	9	3
11	10	5	10	8	1
(ref) 14		(ref) 14			(ref) 14

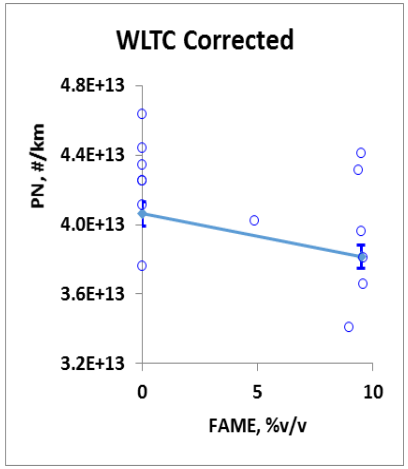
Data Handling

- Failed tests and those deemed invalid due to engineering reasons were rejected and repeated.
- Trend correction was avoided except where essential to reveal fuel effects.
- Fuel property effects were estimated by fitting a simple multiple regression model to each emission with linear terms in the four properties.
- The models were then used to estimate emissions across the measured ranges of fuel properties.









Contents

- Background & Aims
- Test programme overview
- **Results**
  - Density
  - Cetane Number
  - PAH
  - FAME
  - PM & PN overview
  - Particulate matter composition overview
- Conclusions

concawe
ENVIRONMENTAL SCIENCE FOR THE EUROPEAN REFINING INDUSTRY

Results - Density

Density 820 - 855kg/m3	Euro 4	Euro 5	Euro 6
NEDC			
PM (mg/km)	15.49 - 17.47 ***	0.830 - 0.696 NS	0.292 -0.259 NS
PN (#/km)	4.50E+13 - 4.65E+13 **	4.68E+11 - 1.67E+11 ***	3.63E+10 - 2.08E+10 **
WLTC			
PM (mg/km)	13.47 - 15.94 **	0.416 - 0.428 NS	0.192 - 0.163 NS
PN (#/km)	3.78E+13 - 4.10E+13 ***	1.28E+09 - 2.59E+08 **	2.70E+08 - 2.69E+08 NS
90km/h			
PN (#/km)	3.24E+13 – 3.41E+13 **	5.08E+07 - 9.34E+07 NS	6.25E+07 - 6.62E+07 NS
Mean particle diameter (nm)	64.11 - 68.18 ***		

orange	statistically significant decrease
blue	statistically significant increase
black	no statistically significant effect

***	>99.9% confidence
**	>99% confidence
*	>95% confidence
NS	not significant

PM & PN increase with density in the Euro 4 car in all tests & mean particle diameter increases in the steady state test

PN falls as density increases in the Euro 5 & 6 NEDC tests & in the Euro 5 WLTC

concawe
ENVIRONMENTAL SCIENCE FOR THE EUROPEAN REFINING INDUSTRY

Results – Cetane Number

Cetane number 46 - 54	Euro 4	Euro 5	Euro 6
NEDC			
PM (mg/km)	14.79 - 18.17 ***	0.786 - 0.740 NS	0.317 - 0.234 NS
PN (#/km)	4.24E+13 - 4.93E+13 ***	3.00E+11 - 2.61E+11 NS	3.59E+10 - 2.10E+10 **
WLTC			
PM (mg/km)	13.46 - 15.95 **	0.416 - 0.429 NS	0.205 - 0.150 NS
PN (#/km)	3.73E+13 - 4.16E+13 ***	6.62E+08 - 5.01E+08 NS	2.61E+08 - 2.78E+08 NS
90km/h			
PN (#/km)	3.06E+13 - 3.61E+13 ***	6.33E+07 - 7.50E+07 NS	6.95E+07 - 5.95E+07 NS
Mean particle diameter (nm)	63.70 - 68.59 ***		

orange	statistically significant decrease
blue	statistically significant increase
black	no statistically significant effect

***	>99.9% confidence
**	>99% confidence
*	>95% confidence
NS	not significant

PM & PN increase with CN in the Euro 4 car in all tests & mean particle diameter increases in the steady state test

PN falls as CN increases in the Euro 6 NEDC test

concawe
ENVIRONMENTAL SCIENCE FOR THE EUROPEAN REFINING INDUSTRY

Results - PAH

PAH 2 - 7.5% m/m	Euro 4	Euro 5	Euro 6
NEDC			
PM (mg/km)	15.93 - 17.03 *	0.720 - 0.806 NS	0.295 - 0.255 NS
PN (#/km)	4.51E+13 - 4.64E+13 *	2.18E+11 - 3.58E+11 *	2.56E+10 - 2.94E+10 NS
WLTC			
PM (mg/km)	13.92 - 15.49 *	0.442 - 0.402 NS	0.184 - 0.171 NS
PN (#/km)	3.83E+13 - 4.05E+13 **	4.21E+08 - 7.88E+08 NS	2.74E+08 - 2.65E+08 NS
90km/h			
PN (#/km)	3.33E+13 - 3.31E+13 NS	7.99E+07 - 5.94E+07 NS	6.82E+07 - 6.06E+07 NS
Mean particle diameter (nm)	66.07 - 66.23 NS		

orange	statistically significant decrease
blue	statistically significant increase
black	no statistically significant effect

***	>99.9% confidence
**	>99% confidence
*	>95% confidence
NS	not significant

PM & PN increase with PAH in the Euro 4 car in the NEDC & WLTC tests & PN increases in the Euro 5 NEDC test

concawe
ENVIRONMENTAL SCIENCE FOR THE EUROPEAN REFINING INDUSTRY

Results - FAME

FAME 0 - 9.5% v/v	Euro 4	Euro 5	Euro 6
NEDC			
PM (mg/km)	17.55 - 15.41 ***	0.799 - 0.727 NS	0.299 - 0.251 NS
PN (#/km)	4.68E+13 - 4.47E+13 ***	2.97E+11 - 2.63E+11 NS	2.29E+10 - 3.29E+10 *
WLTC			
PM (mg/km)	16.11 - 13.30 ***	0.442 - 0.402 NS	0.188 - 0.167 NS
PN (#/km)	4.06E+13 - 3.81E+13 ***	5.15E+08 - 6.44E+08 NS	2.74E+08 - 2.65E+08 NS
90km/h			
PN (#/km)	3.45E+13 - 3.20E+13 ***	6.70E+07 - 7.09E+07 NS	6.21E+07 - 6.66E+07 NS
Mean particle diameter (nm)	67.53 - 64.77 ***		

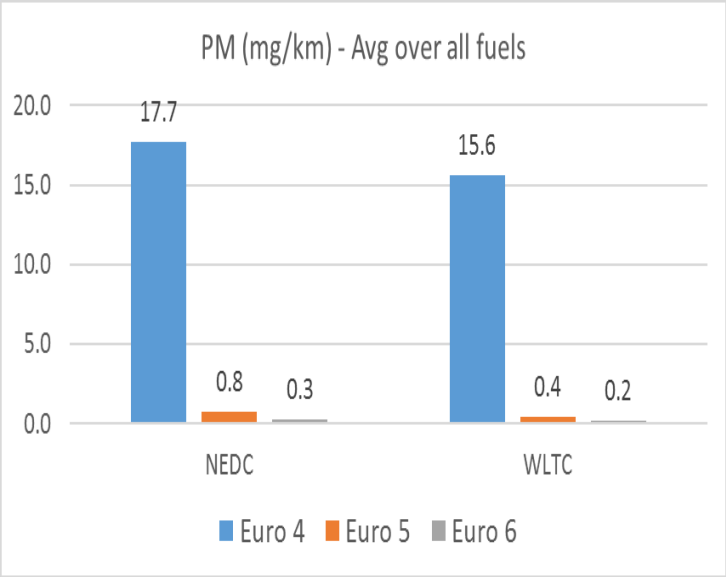
orange	statistically significant decrease
blue	statistically significant increase
black	no statistically significant effect

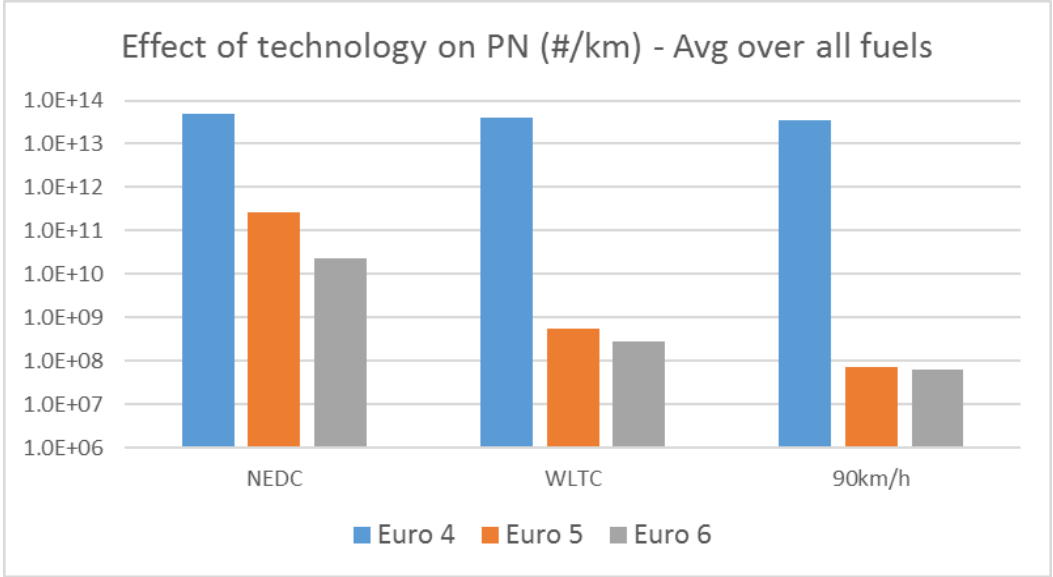
***	>99.9% confidence
**	>99% confidence
*	>95% confidence
NS	not significant

PM & PN fall as FAME increases in the Euro 4 car in all tests & mean particle diameter decreases in the steady state test

PN increases in the Euro 6 NEDC test

PM & PN overview



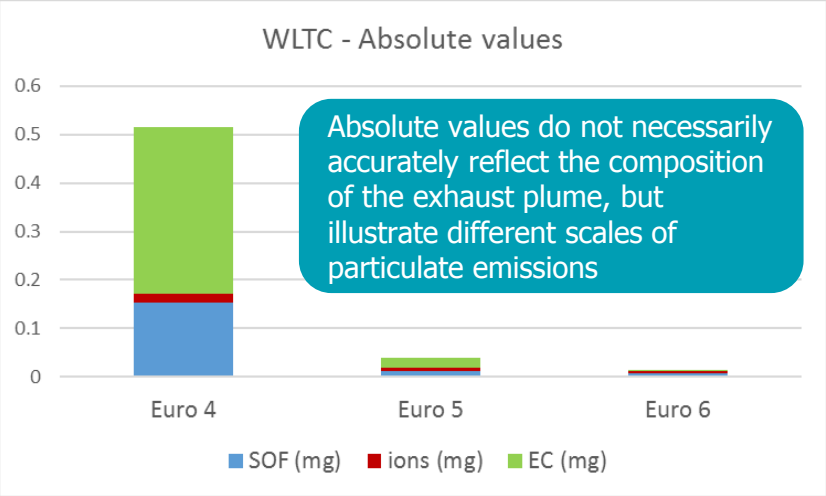


	NEDC		WLTC	
Maximum fuel effects on PM (mg/km)	min	max	min	max
Euro 4	13	22	11	21
Euro 5	0.5	1	0.3	0.5
Euro 6	0.1	0.4	0.1	0.2

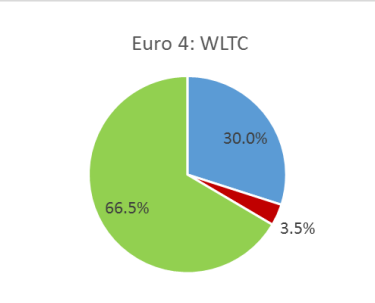
	NEDC		WLTC		90km/h	
Maximum fuel effects on PN	Min	Max	Min	Max	Min	Max
Euro 4	4.0E+13	5.2E+13	3.4E+13	4.6E+13	2.8E+13	3.9E+13
Euro 5	6.7E+10	5.2E+11	1.5E+08	1.5E+09	2.6E+07	1.6E+08
Euro 6	1.1E+10	5.0E+10	1.6E+08	4.0E+08	4.3E+07	9.1E+07

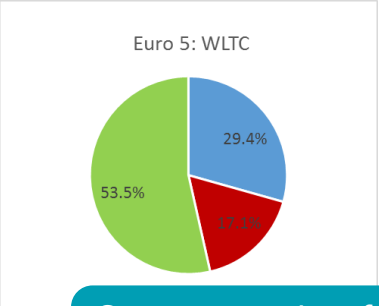
The use of a DPF greatly reduces PM and PN and has a much larger effect than fuel quality

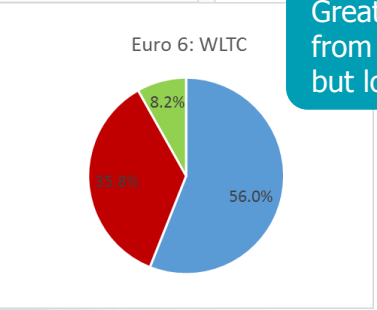
Particulate matter composition overview



Absolute values do not necessarily accurately reflect the composition of the exhaust plume, but illustrate different scales of particulate emissions

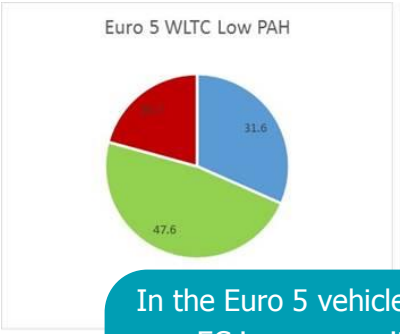






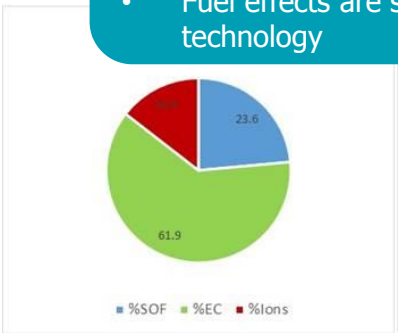
Greater proportion of ions from DPF vehicle samples but lower absolute levels

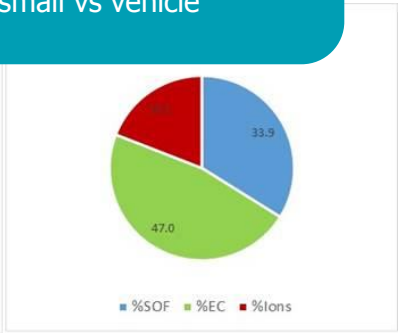
No statistically significant fuel effects on PM composition in the Euro 4 or Euro 6 vehicles…….



In the Euro 5 vehicle:

- EC increases with PAH
- Ions and SOF content increase with density
- Fuel effects are small vs vehicle technology





Contents

- Background & Aims
- Test programme overview
- Results
- **Conclusions**

Conclusions

To better understand topical diesel fuel property effects in the European light duty fleet, Concawe has conducted a test programme on single Euro 4, 5 and 6 vehicles. Findings include:

- Increasing density from 820 to 855kg/m^3 and CN from 46 to 54 fuels tended to produce higher PM and PN and particles of larger mean diameter in the non-DPF Euro 4 car but fewer particles from the DPF-equipped Euro 5 and 6 vehicles in some cases.
- Increasing PAH from 2 to 7.5%m/m also tended to produce higher PM and PN in the non-DPF car. The DPF-equipped vehicles appeared largely insensitive to changes in PAH.
- Increasing FAME from 0 to 9.5%v/v tended to produce lower PM and PN and smaller mean diameter particles in the non-DPF car. The DPF-equipped vehicles appeared largely insensitive to changes in FAME.
- The proportion of ions in the particulate matter is substantially higher and elemental carbon substantially lower in the Euro 6 vehicle vs the Euro 4 and 5. Fuel had little effect on particulate composition.
- Overall the effect of vehicle technology dominated fuel effects on particulate mass & number emissions.